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Automatic Inspection and Diagnostic Systems for Automotive Equipment

G. Staton, A. Chalfin,
and R. J. Brachman

U. S. Army Ordnance - Frankford Arsenal

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Automatic Inspection and Diagnostic Systems for Automotive Equipment

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THE SOLUTION to the problem of developing a maintenance force to serve land automotive equipment is a matter of improving the quality of the individual mechanic rather than of increasing the number of maintenance personnel. "The fact that industry is currently faced with a shortage of maintenance personnel will affect the armed services in the long run. Thus, trained mechanics will not be available to augment the peacetime maintenance force in national emergency. In any future war, the Ordnance Corps will experience an unprecedented shortage of automotive mechanics. This will be a reflection of the shortage currently existing in civilian life today, coupled with the increased complexity of modern automotive material." These comments have been extracted from a study relating to maintenance criteria for tank-automotive vehicles. The personnel problem, coupled with the fact that there are extremely heavy incident rates of failures at the early mileage of vehicle, warrants that the Ordnance Corps make a major effort to receive, service, and adjust all new and remanufactured vehicles prior to use. These two related problems present the Ordnance Corps with an almost insurmountable problem. To complicate matters further, many vehicles or automotive components returned for repair are still very serviceable and require adjustments only. Current procedures for major inspection and overhaul require the removal of the major automotive subassemblies and further dismantling of these assemblies to perform a detailed mechanical inspection of all parts. Obviously this disassembly cannot be handled at any direct support level in the field. At the present, this work is done at rebuild depots where skilled mechanics, tools, and handling equipment provide the facilities to tear down automotive components.

In 1960 Frankford Arsenal, through the Chief of Field Service, proposed a program to couple modern computer technology with the maintenance problem, in order to provide a diagnostic tool that would permit less skilled personnel to inspect and diagnose automotive components without teardown.

In order to prove the capability and usefulness of the diagnostic system proposed by Frankford Arsenal, the Chief of the Maintenance Division, Ordnance Field Service, presented a problem to test the proposal. The problem was basically stated as follows:

"The test set will analyze and diagnosis malfunction in the power pack (which is the engine, the transmission and oil cooling system) of an M48 tank without removal or modification of the power pack. The system will be operable by low skilled personnel, not present a maintenance problem of its own, and be sufficiently easily used to materially improve the inspection rate of vehicles through the rebuild depot."

VEHICLE CHECKOUT SYSTEM

SYSTEM DESCRIPTION: General Overall - The system proposed to meet the requirements for solving the above problem was designated a computer-control checkout system. For some time Frankford Arsenal had been working in multisystem test equipment for electronic chassis and electronic components. A number of automatic and semiautomatic systems used in the United States today utilize punch paper tape or magnetic tape and are serial-programmed for sequentially operating, testing, and comparing data in order to determine whether the component under test is ac-

ceptable. The major drawback was that these systems could compare only a given reading with a single stored value. The evaluation thus had to be made on this one reading only. The lack of memory and arithmetic capabilities meant that many malfunctions could not be diagnosed, since many measurements have to be taken, stored, and then compared to other data acquired at a later time or to a series of data evaluated around a mean or normal. Absolute data with tolerances were not available for comparison when used in a standard "go-no-go" test. The computer technology had advanced sufficiently so that there was no question that a low-cost, simple, digital computer could be coupled with the control and switching system for vehicle checkout. This would be a major step forward and could represent a technological breakthrough in the maintenance art. The computer contained all the features necessary for performing the complete system test, analysis, and diagnosis of the data. Based on previous predetermined and stored symptoms or information, it could provide the mechanic with a complete set of instructions in the form of a printed record of the malfunction, its location, its part number, and where replacement was located in the supply system.

Several problems were immediately apparent at the outset of this program. Two of the most pressing were accessibility (in view of the "no modification" ground rule) and a suitable method of dynamic exercising.

Fig. 1 is an actual photograph of the installed powerpack of the tank with the grilles removed. It can be seen easily that the entire lower portion of the engine is inaccessible and that reaching the cylinder heads is not a simple task. The solution to this problem (as with most of its type) required a number of trade-offs between desired measurement location and accessible areas, in addition to a series of spe-

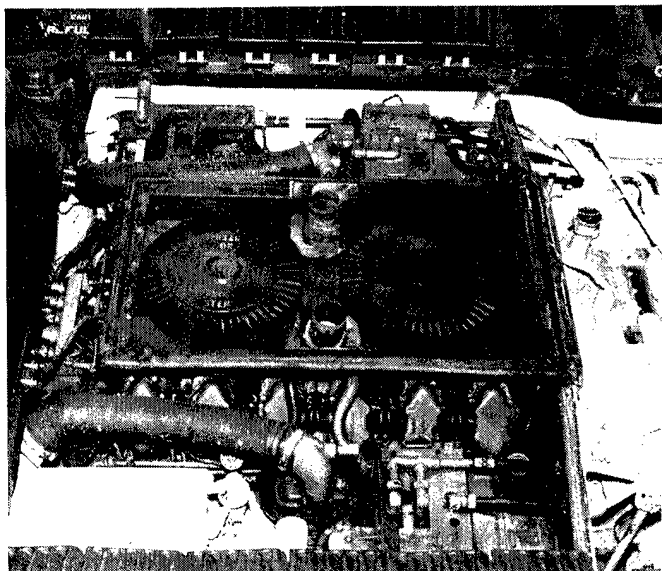


Fig. 1 - Power pack, M48 tank

cially devised fixtures to facilitate placement.

There has been general agreement in the maintenance field for some time that the final test of an engine and drive system must be at full rated load. When the vehicle is a 50-ton, track-laying variety capable of developing a total of 80,000 ft-lb of torque at the sprockets under stall conditions, the problem becomes very complex. Feasibility studies were initiated on various means of producing and controlling the desired loads on the vehicle. The results of these studies indicated the most feasible method to be a sprocket dynamometer with special provisions for rapid hook-up of the vehicle. Unfortunately the estimated cost of this approach precluded its incorporation into the system at that time. As an expedient, to overcome the economic impasse, the installation shown in Fig. 2 was designed. This arrangement, to be used for the initial tests only, was a standard engine dynamometer cell for an out-of-vehicle test and a modification of a standard cell to handle an out-of-vehicle power pack.

The system described in this paper is capable of performing a diagnostic test on an engine alone, a power pack alone, or a power pack in the vehicle, without any hardware modifications. The only change required is a small modification of the computer program. To keep within the narrow scope of this paper, the case discussed is that of the system for testing the engine alone.

In general the description will follow the functional division of the project; that is, into controller development, instrumentation design, and development of the diagnostic program.

In recent years the trend toward automation has been increasingly affecting the field of testing and checkout. Regardless of the type of materiel being tested, certain basic functions are required by any automatic testing system. It is necessary to review briefly these basic functions and the interpretation used, so that the approach discussed in this paper may be more clearly understood. These basic auto-

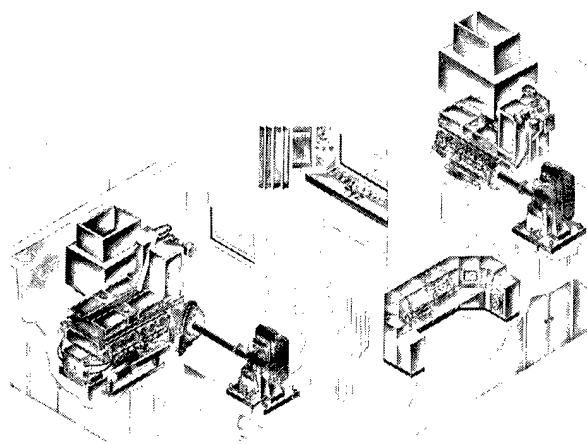


Fig. 2 - Letterkenny Ordnance depot installation

matic testing functions are explained in the following paragraphs.

1. Program-An automatic testing system must make provisions for a sequence of steps that tells the machine which tests are to be performed. In addition the program includes data that describe the test limits against which test results are to be compared. This program can take the form of switches, punch paper tape, punch cards, magnetic tape, magnetic drums, wire patchboards, and so forth.

2. Control-This function of the test equipment is required to accept the information contained in the test program and to translate it into the physical activity required to accomplish the desired tests. It includes, where necessary, the proper stimulation of the item under test.

3. Switching-This is a major operational portion of an automatic test system control and provides the interconnection of measurement and stimulation of the item under test.

4. Measurement-Testing requires a measurement of some characteristic or physical parameter by which the performance of the item under test is to be evaluated.

5. Conversion-Measurements of the testing parameters must be converted into a suitable form for handling by the automatic test system. Most phenomena are in the form of proportional (analog) signals. These data must be converted to digital form suitable for use by the controller.

6. Storage (Memory)-In a conventional test system the storage or memory function is not always clearly defined. In the minimum case, temporary storage for the data from a single measurement prior to evaluation is provided. The storage in most cases is either in the form of program tape, a register, or a comparator. The extremely small memory capacity of most automatic test systems is the primary limiting factor in the overall capability of the system.

7. Evaluation-The entire purpose of the previous functions is to obtain a measurement in a form suitable for evaluation. This measurement in most automatic systems is merely compared against some stored limit. In the equipment to be described, the ability to perform a mathematical evaluation of test results is a major capability existing in no other system.

8. Communication-The automatic test system must provide some facility for the communication of test results to the operator. This is usually accomplished by Go-No-Go lights and printed hard copy.

The conventional automatic test systems that provide the above functions are classified, for purposes of discussions, as serial-programed systems. The serial-programed, automatic test system is characterized by the use of punch paper tape, punch card, wire patchboard, or magnetic tape as a programmer that controls its operations. This controller is able to energize special stimuli and excite the unit under test. After proper stimulation, a measurement is made, and the result of this measurement is compared with tolerance values obtained from the programmer for a "low-go-high" indication of the measurement value. It must be emphasized

that this measurement is based on a single test result, and consequently the comparison is made on the basis of the single test value. For the measurement to have some value in diagnosing component failure, it must have a unique relationship to a component of the unit under test. In order for this to be true, the component must be isolated from the effect of other components in the unit under test. In most classes of materiel to be tested, and particularly in the automotive type of equipment, this isolation is rarely obtained. In actual fact, to determine if a component is malfunctioning in a system, its performance must be evaluated in conjunction with many other components and system performance data. For this reason the degree of component failure detection and piece-part fault isolation which a serial-programed system can accomplish is a mere accident of the component accessibility and operational isolation in the unit under test. This serious inherent limitation of the serial-programed, automatic test equipment would make impossible the utilization of a low-skill level of maintenance personnel, a primary objective of test automation.

It was for this reason that the computer equipment discussed in this paper was developed. The objective of the development was to demonstrate that a digital-computer-controlled, automatic test system could provide a solution to the specific problem of maintenance of military vehicles.

A computer-controlled checkout system is capable of performing not only all the testing functions of the serial-programed system but others as well. For instance, the computer-controlled system uses the computer memory as the basic programmer storage. It is also capable of energizing necessary stimuli and performing measurements on the unit under test. In addition the computer is able to store a series of measurement values in its memory and, after completion of a series of tests, to evaluate these test results and diagnose component failure. This evaluation is actually an analysis of the test results, made automatically, either mathematically or by some logic or inductive process. Having accomplished its evaluation and determined the most likely or exact cause of fault, it is then able to print out the components to be replaced, repaired or adjusted, with specific repair instructions. The important point to be noted is that it is possible with computer-controlled, automatic test equipment to perform much greater piece-part fault isolation than with the conventional serial-programed systems, since the computer utilizes an interrelation of a number of measurements to diagnose malfunctions. This is the method employed by the most skilled maintenance personnel. Since this interrelation of measurements is preprogramed into the computer as a result of a complete analysis of the unit under test, the intelligence of the designer and the best malfunction diagnostician are in effect incorporated into the test system performance.

In summary, the computer-controlled, automatic test system has the capability of performing an analytical evaluation of a spectrum of test results. From this evaluation

it makes specific fault diagnosis of the unit under test at the piece-part level. In the conventional serial-programed systems, the analysis of test results must be accomplished by a skilled, highly trained diagnostician who reads from the tape of printed-out test results and draws conclusions as to the component at fault.

Controller - Insofar as the computer-controlled, automatic test system concept is concerned, any number of general purpose digital computers can be used in the system control. As a matter of fact, the initial system designed used a small military computer, the Verdant. However, due to prior commitments for the Verdant instrument it became necessary to select a different computer. The Libratrol 500 computer, manufactured by Librascope, Inc., was chosen on the basis of availability and cost considerations. A new design was also investigated, and a specification has been written, using the FADAC and 6-cu ft militarized digital computer. (See Fig. 3.)

Description of System Control-A functional block diagram of the system control is shown in Fig. 4. The functional blocks in the figure are numbered and correspond to

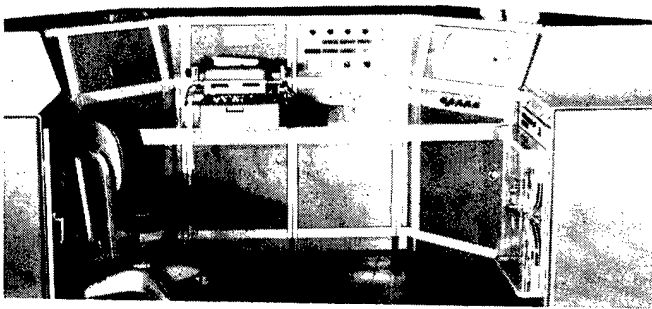


Fig. 3 - Controller console (with Libratrol 500)

the paragraph numbers listed below. It should be noted that in the actual equipment, several functional blocks are combined and time is shared to perform their functions. In addition, different functions described separately within a given block use the same circuitry on a time-shared basis.

1. **Arithmetic and Control**-This section is the heart of the Libratrol 500 computer and consequently is the heart of the automatic test system control console. The arithmetic and control section contains the circuits that perform arithmetic operations, timing, and control of information transfer in the system.

2. **Drum Memory**-The drum memory provides the working memory for the system control. This section provides for test program storage as well as storage for measurement and computation values. The drum provides 64 tracks of 64 words per track. The word size is 31 bits, including sign. One track is an input-output buffer track that accepts digital data from the converter, information from the digital inputs, and identification pulses. Digital codes being transferred to the output relays are also routed through this track.

3. **Manual Control Panel**-This facility permits manual control of the computer, as well as monitoring of appropriate registers throughout the system. The monitor facility is provided by a special register display panel. The display, consisting of 32 neon lights, is capable of displaying the contents of either the A, C, or R registers of the computer by means of a selector switch. This display is used primarily during the initial programming of the computer and during maintenance, and is therefore covered by a panel when not in use.

4. **Input Address (Group Selection)**-The d-c voltage inputs to the system from the unit under test are provided by a relay commutator, to be described later. Control of the

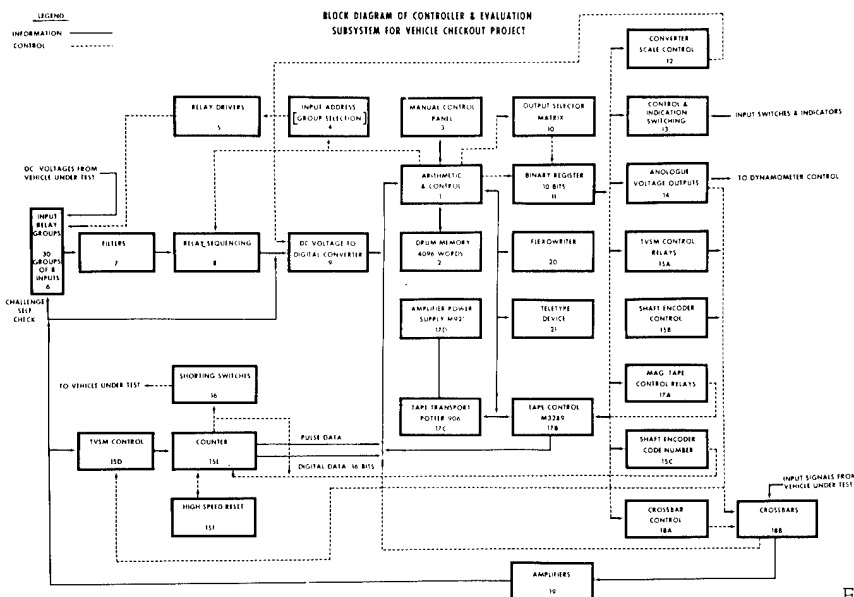


Fig. 4 - Subsystem for vehicle checkout project

commutator is effected by this section. The d-c voltage inputs are normally selected in groups of eight. The input address register in this section selects the particular group of eight inputs to be connected to the system input.

5. Relay Drivers-This section furnishes the power amplification necessary to drive the relays in the commutator section in accordance with signals provided by the group selection circuitry.

6. Input Relay Groups-The input relay groups form a commutator assembly. Each group of relays consists of eight inputs connected to a common bus by four-pole, double-throw, mercury-wetted relays. Thirty such groups presently exist in the system, which provides the capability for 240 inputs. This capability can easily be expanded in groups of 120 inputs each, if desired. In the event that an input measurement yielded an out-of-tolerance reading, the crossbar switch (section 20) would automatically present that particular input with an in-tolerance voltage (or a fixed voltage). This provision comprises an automatic self-check of this portion of the system before the tests can continue.

7. Filters-The eight lines selected by the energizing of two relays of a particular input group are connected via eight busses to eight special filters. The filters provide for rejection of 60-cps noise on the input lines. An "M"-derived, low-pass filter with 30 cps as the 3-db downpoint is used.

8. Relay Sequencing-This section incorporates eight relays that are continually being sequenced in such a fashion as to scan the eight lines of the particular input group selected. These relays thus connect the converter with each of the eight incoming lines in a fixed sequence.

9. D-C Voltage, Analog-to-Digital Converter-This section of the system converts the d-c voltages on the input lines to digital information that can be used by the computer. In the system under discussion, an Adage Voldicon, Model VR 10AB, is used. This converter is modified for use with the Libratrol 500 computer. Full-scale ranges of 1 and 10 volts are possible. Circuitry for automatic scale selection by the computer is provided. The input impedance of this equipment is approximately 1000 megohms. There are two modes of operation of the converter in this system; one mode samples eight input lines at a rate of 75 conversions per sec, and a high-speed mode samples the same input line at a rate of 2000 conversions per sec.

10. Output Selector Matrix-A five-bit decoder matrix is used to determine which output relay bank is to be selected. The system includes 20 relay banks of 10 relays each. This quantity is expandable up to 32 banks if desired. The 200 output relays presently provided are available for all currently anticipated computer control requirements.

11. Binary Register-This register determines which relay or relays in the output relay bank selected are to be activated. The register is ten bits in size. The relays controlled are of the magnetic latching type, to permit relay latching when the binary register is cleared.

12. Converter Scale Control-This section is provided by the output relays and serves to control the range selection on the d-c voltage, analog-to-digital converter.

13. Control and Indication Switching-This section refers to the function of those blocks of output relays that serve to perform the "on-off" type of switching used in various check-out controls and in the activation of special indicators. For example, these relays will control the malfunction alarms and indicators used in the system.

14. Analog Voltage Outputs-Five of the output relay banks are set aside to provide for a digital-to-analog voltage conversion. Each bank of ten relays can be used to generate an analog voltage of the digital number in the binary register (block 11) by wiring the relay contacts to form a resistive voltage divider network. Impedance and voltage levels are easily designed to match the application. The use of three of these programmable analog voltage generators is assigned to the control of the dynamometer used in the system. The remaining programmable voltage generators are reserved for self-checking and in the time-varying measurement section.

15. Time-Varying Signal Measurement (TVSM) Section-The time-varying signal measurement section hereafter referred to as the TVSM section) is shown in Fig. 4 as a number of separate blocks numbered (15A) through (15F). The section consists primarily of three differential amplifiers, two binary counters, one megacycle precision oscillator time standard, and the associated control and interface circuitry required for complete automatic operation under computer control.

The modes of operation provided by the TVSM section are as follows:

- (a) Time per N time units
- (b) Time per M events
- (c) Events per M events
- (d) Time per M events with N independent event delay
- (e) Time per M events after N independent events
- (f) Events per M events after N independent events
- (g) N event duration pulse with M event delay repetitive

Since the threshold voltage used to define M and N events is programmable, the TVSM section can also be used to determine rise time and peak voltages of the time-varying signals.

15A. TVSM Control Relays-One output relay bank is used to determine the mode of operation of the TVSM section.

15B. Shaft Encoder Control Relays-This output relay bank is used to program the TVSM control section, primarily when the TVSM section is used as a control device and not as a measurement or information section. For example, the shaft encoder control enables the TVSM section to stop the high-speed conversion mode and permits special shorting operations to be performed at different angular positions of the engine crankshaft.

15C. Shaft Encoder Code Number-This section is used

to preset two numbers into the counters of the TVSM section which define the angular rotation of the crankshaft during which high-speed measurements are to be made. When the counter counts down to zero, it transmits a pulse that will be used to mark the measurement.

15D. TVSM Control-The TVSM control contains the storage elements for determining the operating mode, the differential amplifiers as well as the output polarity selector circuits, together with the counter overflow detectors, and to start signal detectors. The control circuitry is used to sequence the loading of the various counters and to provide the computer with output signals consisting of overflows, count accumulations, terminate and verify signals.

15E. Counter Section-The counter section consists primarily of two counters. The first counter is a 16-stage counter and the second counter is an 8-stage counter. Both counters can operate at a rate of 1 mc frequency. The oscillator is also provided in this section.

Overflow from the counters is transmitted automatically to the computer memory. The counter registers are sampled by the computer via the digital inputs of the magnetic drum input channel.

15F. High-Speed Reset-In some cases, after the counter in the TVSM section has counted down and provided an output signal, it is necessary to preset the counter very quickly. Normally the counter is preset by the computer. In these special cases this normal presetting is too slow. The reconstituting logic presets the counter without the delay inserted by the computer. This is accomplished by using one of the two counters as a temporary memory for the desired presetting value. The counter to be used for counting is then set to this value without recourse to the computer program, thus eliminating the computer delay.

16. Shorting Switches-These switches allow shorting of various input lines from the engine as a function of the angular position of the crankshaft. This feature is completely under program control of the computer and can repeat the same short until changed by the program.

17. Magnetic Tape Storage System-The magnetic tape storage system is shown in Fig. 4 as blocks (17A) through (17D). This memory system augments the computer magnetic drum and provides the equivalent of approximately 75 drum loads in a single 10-in. reel of magnetic tape. This additional memory capacity permits the storage of the required programs and logistical data. The magnetic tape storage system is under complete control of the computer, with automatic search, read, and write capabilities.

17A. Magnetic Tape Control Relays-This section consists of computer output relays that serve to control the on-off, read-write, fast-slow clutch engagement, and forward-reverse selection of the magnetic tape transport. In addition, this section presets the address of the desired information on the magnetic tape.

17B. Tape Control-This section contains the logic circuitry required for search and also the buffering necessary

to write on, or read from, the magnetic tape.

17C. Tape Transport-The tape transport used in the system is a Potter Model 906 modified to search at 100 in. per sec, read at 5 in. per sec, and write at 2-1/2 in. per sec. The transport permits forward or reverse operation.

17D. Amplifier Power Supply-This section provides the special supply voltages required for proper operation of the magnetic tape storage system.

18. Crossbar Switching System-The crossbar switching system is shown in Fig. 1 as blocks (18A) and (18B). This switching system is used for switching of the time-varying signals as well as for the automatic check of the commutator assembly.

18A. Crossbar Control-A group of output relays is used to control the activation of the crossbar switch.

18B. Crossbar Switch-A 20 x 10 x 6 connections, Cunningham Type F crossbar switch is wired in groups of 50 to 75 inputs per "hold" function. There are 20 such "hold" functions in a crossbar switch. Crosspoint activation is checked by the computer. The crossbar is used to route analog information signals to the TVSM section, to route input voltages to the converter for high-speed conversion, and to present a given input line with a programed or fixed voltage.

19. Amplifiers-Amplification is required for vibration transducers and low-level signals. The exact number of such amplifiers is dependent on the exact number of these types of measurements employed.

20. Flexowriter-The Flexowriter is normally used to address the computer, both by keyboard and through a paper tape reader. It also provides a punch output. The Flexowriter will be used to type out test results and logistical information as commanded by the checkout system.

21. Teletype Device-Provision has been made to use a conventional Signal Corps teletype as an auxiliary system output device. This output will not be used in the initial operation of the system but may be added at a later date.

Instrumentation Subsystem - The instrumentation subsystem consists of transducers, special bracketry, stimuli, and wave-shaping circuitry. Its function is to detect those signals indicative of performance, transduce them into electrical signals, and modify them to acceptable inputs for the controller. The subsystem is completely free-running; that is, the signals are always present, and reading them merely requires switching in an appropriate measuring device. The specific measurements made are shown in Table 1. In all, there are 61 measurements made on the engine. Many of these are redundant in some respects when considering a single malfunction; however, in case of multiple faults, they serve to separate the specific faults when grouped and to add reliability to the system as a whole.

All the transducers listed are modifications of commercially available units that, through a series of tests, have been selected to meet most nearly the desired characteristics. Some of the criteria used in this selection were rel-

Table 1 - Table of Measurement Subsystems

<u>Subsystem</u>	<u>Sensor Location</u>	<u>Number of Points</u>	<u>Measurement Principle</u>	<u>Sensor Type</u>	<u>Purpose of Measurement</u>
Temperature	Spark plug insert	24	Variable resistance	Special probe	Cooling and power system analysis
	Oil sump	1	Variable resistance	Immersion probe	Lubricating system analysis and safety monitor
	Carburetor intake	2	Variable resistance	Immersion probe	Correction factor
	Ambient	1	Variable resistance	Immersion probe	Correction factor
	Fuel line	1	Variable resistance	Immersion probe	Correction factor
Pressure	Intake manifold	2	Variable resistance	Potentiometer	Intake system analysis
	Oil galleys	1	Variable resistance	Installed sending unit	Lubricating system analysis and safety monitor
	Ambient	1	Variable resistance	Potentiometer	Correction factor
	Breathing system	1	Variable resistance	Potentiometer	Engine wear (blowby)
Vibration	Valve cover	12	Magnetostrictive	Special	Valve action analysis
Ignition	Terminal block	4	Special filter circuit	Direct tie-in	Ignition system analysis
Flow	Fuel supply line	1	Turbine	Magnetic	Intake system analysis
	Carburetor air intake	2	Variable resistance	Flow tube	Intake system analysis
Position	Crankshaft	1	Photoelectric	Special	Time and trigger base
Speed	Engine	1	Magnetic	Tachometer	Basic control
	Dynamometer	1	Magnetic	Tachometer	Basic control
Velocity	Engine cooling fan	2	Variable resistance	Special	Cooling system analysis
Weight	Ext. add δ weigh system	1	Variable resistance	Potentiometer	Engine wear (oil consumption)
Torque	Dynamometer	1	Variable resistance	Load cell	Basic control
Horsepower	Dynamometer	1	Computed	Circuit	Basic control
Humidity	Ambient	1	Variable resistance	Special	Correction factor

atively high output, long life under combined environments, accuracy, interchangeability, cost, and standardization of basic measurement principle.

(a) Outputs of the sensors were fixed by the design to be 0 to 1 v d-c and 0 to 10 v d-c for all steady-state measurements and -10 to +10 v for the time-varying signals. By selecting the proper combination of excitation voltage and transducer characteristics, the normal range of sensed variable lies between 0.25 and 1.0 v d-c and 2.5 and 10.0 v d-c for the steady-state cases. Thus the overall measurement error on d-c measurements has been held below 5%. In most cases it is the order of 1%.

The transducers are housed in a specially designed set of cabinets that are lowered over the engine so as to position the sensors approximately. Each transducer is mounted on a bracket that allows the installing technician to place it properly in a minimum of time. Fig. 5 shows an actual trial installation in progress. Estimated time for instrumentation appears conservative at 30 min. It seems likely that, with practice, this time can be significantly reduced. A number of transducers and their placement are shown in sketch form in Figs. 6 - 16B.

Oil Flow Measurement-The basic "ground rule" of not breaking lines to obtain desired measurements resulted in an investigation of methods for measuring lubricating oil flow in pipes by external means. A complete investigation proved that no such method was available and that no work on this problem was in progress. The most feasible idea for effecting this measurement appeared to be one based on the effect of flow on the heat transfer of a short length of pipe with a line heat source input.

The concept is that if a line source of heat is applied to the outside circumference of the pipe, and the surface temperature is maintained at a fixed value above the oil temperature in the pipe, then the downstream temperature of the pipe surface should be a function of the flow rate. The above statement is based on the fact that variants affecting heat transfer for this case are:

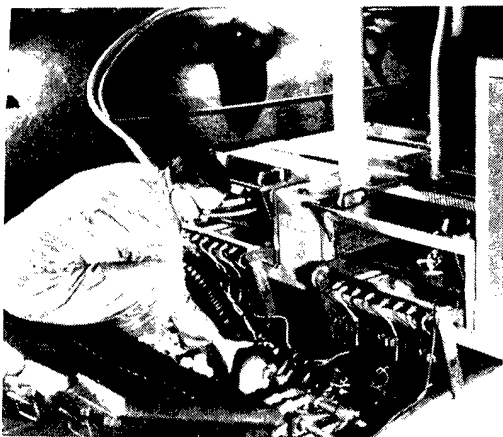


Fig. 5 - Transducer installation

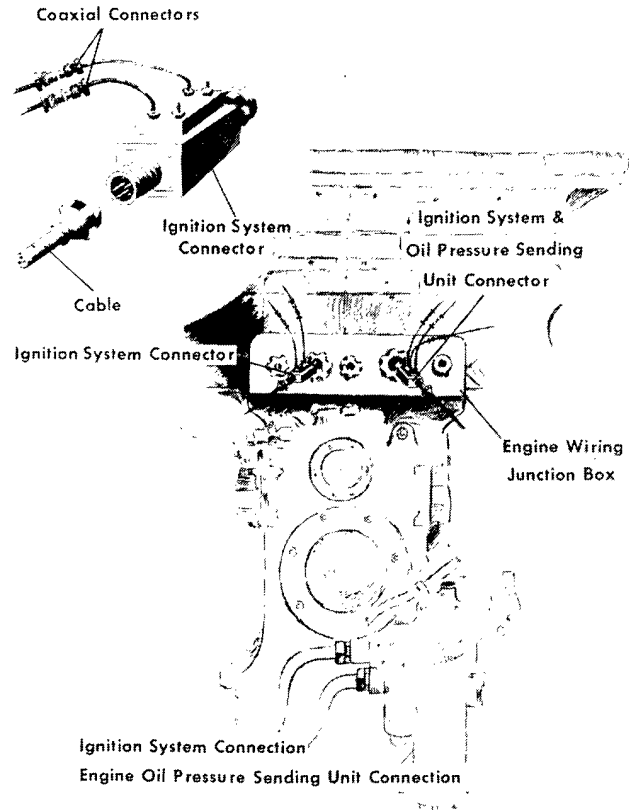


Fig. 6 - Instrumentation subsystem

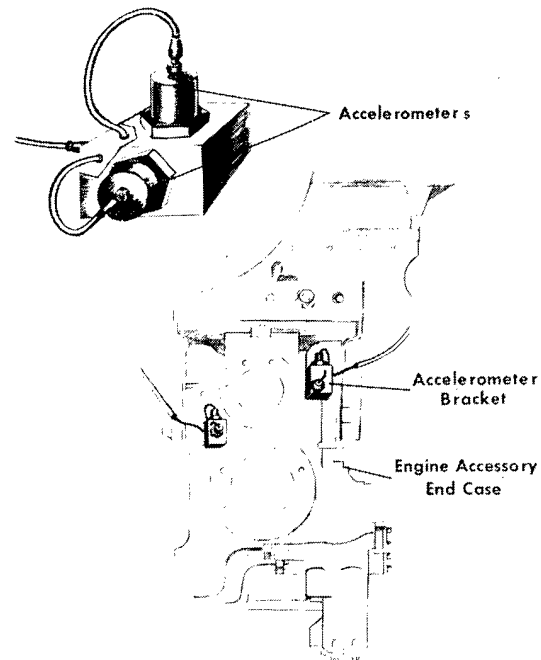


Fig. 7 - Accelerometer installation; engine block vibration

(1) Temperature differential between the fluid and the pipe.

(2) Velocity of fluid flow.

(3) Fluid viscosity.

(4) Fluid specific heat.

(5) Fluid thermal conductivity.

(6) Fluid heat-transfer film coefficient.

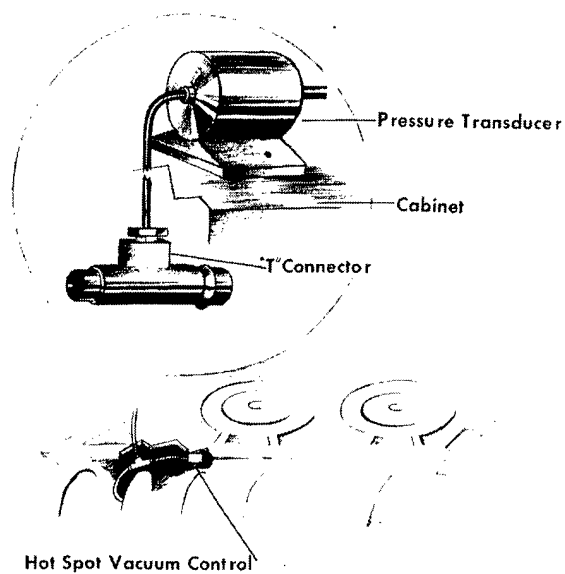


Fig. 8 - Intake manifold pressure

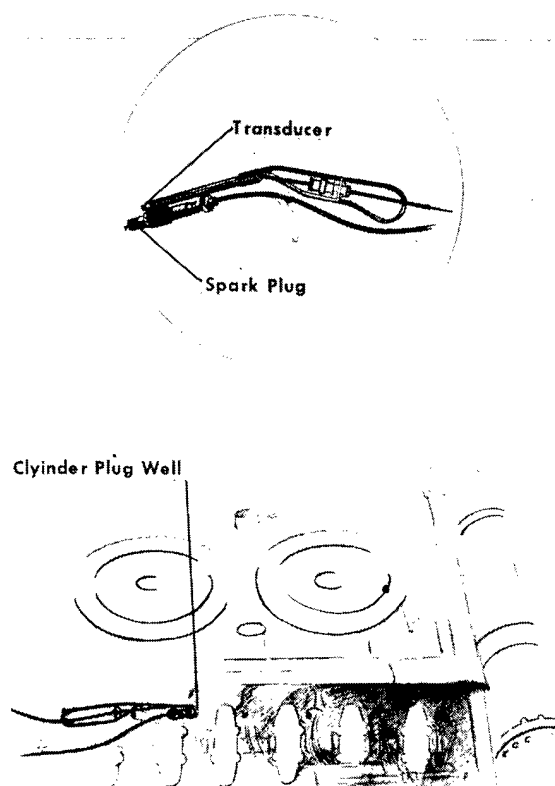


Fig. 10 - Cylinder head temperature

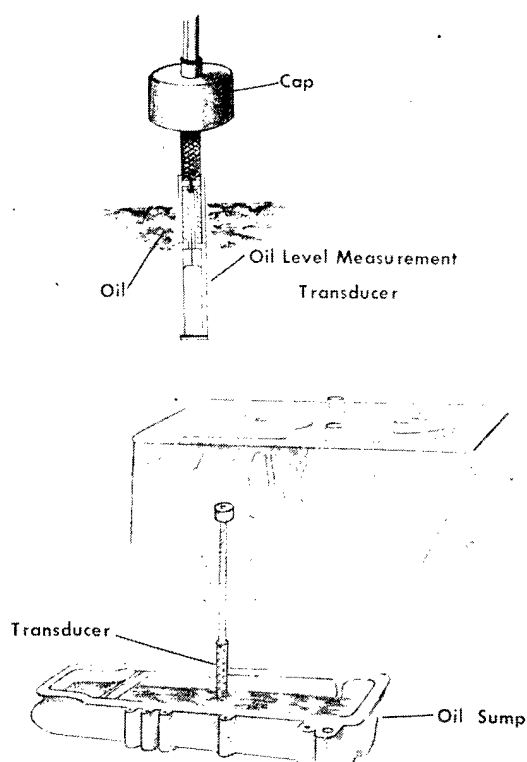


Fig. 9 - Oil consumption measurement

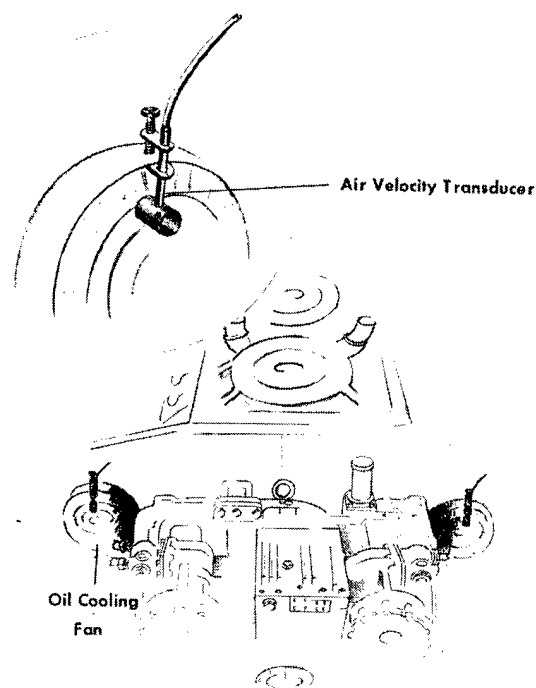


Fig. 11 - Air velocity; oil cooler fans

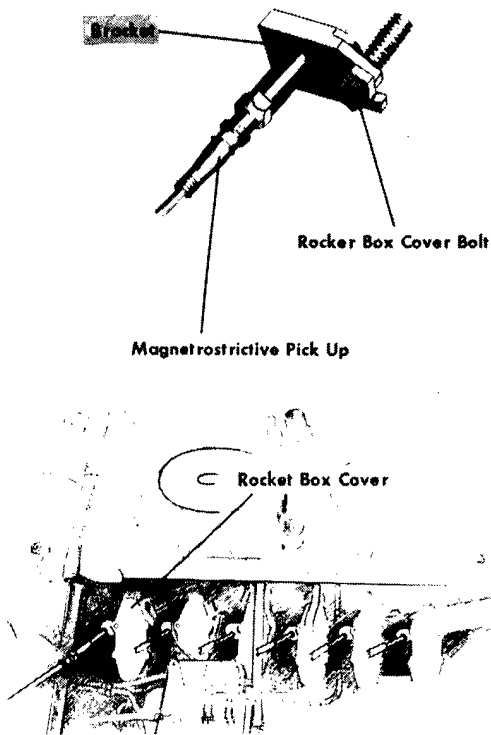


Fig. 12 - Engine cylinder vibration

It may therefore be seen that if (1) is controlled externally and (3), (4), (5), and (6) are known (since they are functions of fluid temperature), then the temperature gradient along the pipe as a measure of the heat transfer will vary only as a function of the fluid flow.

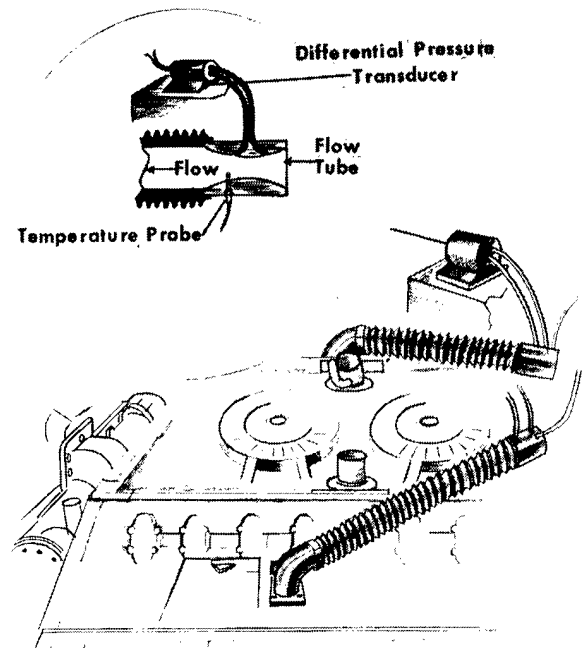


Fig. 14 - Intake air flow and temperature

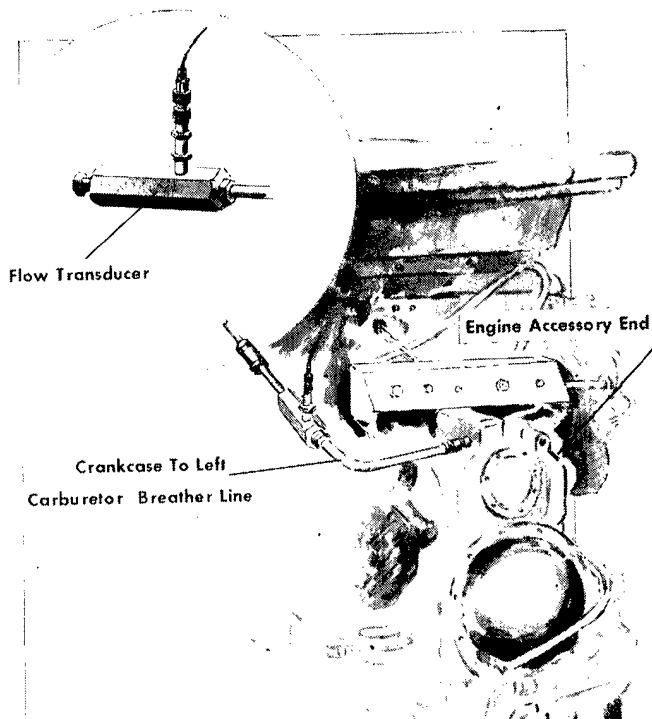


Fig. 13 - Engine blowby

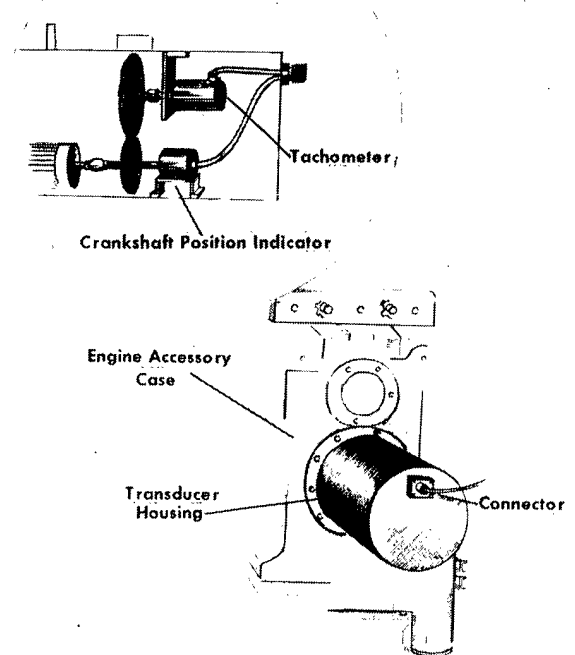


Fig. 15 - Crankshaft position indicator; engine speed

Fig. 17 is a schematic of the oil flow measurement. Fig. 18 is a sketch of the transducers.

(b) The loading device for the first application is a standard 1200 hp eddy current engine dynamometer. Modifications have been made in the power amplifier of this machine to provide additional field forcing and to make it adaptable to automatic control. Controls have been designed to regulate any two of speed, load, and throttle positions over the entire range of operation.

Performance specifications for this control system are:

(1) Hold speed constant at values between 650 and 2800 rpm, ± 7.5 rpm, steady-state and long-term repeatability, and ± 30 rpm during load upsets of up to 2000 ft-lb. The rate of change of load will not be in excess of 335 ft-lb per sec.

(2) Hold torque output constant from friction level to

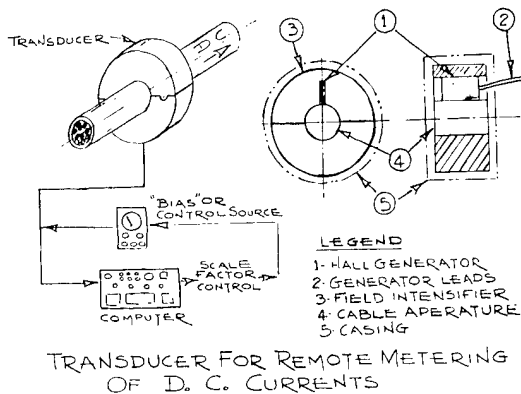


Fig. 16a - Transducer for remote metering of d-c currents

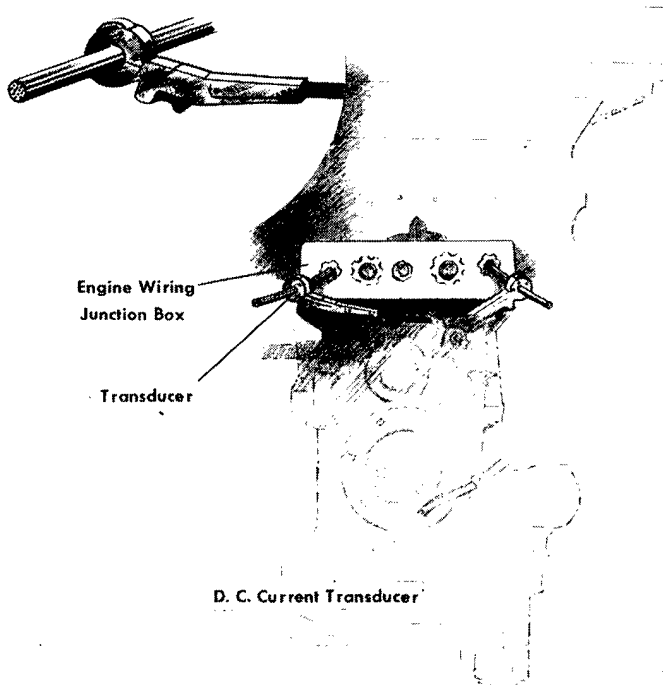


Fig. 16b - D-c current transducer

2000 ft-lb, ± 5 ft-lb, steady-state and long-term repeatability, and ± 20 ft-lb during speed upsets from 650 to 2800 rpm. Rate of change of engine speed to be not in excess of 1700 rpm per sec.

(3) Hold throttle position constant $\pm 1/4\%$ of full travel, steady-state and long term repeatability, and track with 1% during full travel actuation in 0.5 sec.

(4) Program speeds from 650 to 2800 rpm and loads from friction level to 200 ft-lb simultaneously. Transient tracking accuracies to be ± 30 rpm and ± 20 ft-lb.

With this type of engine control system coupled to the main controller, it can be seen readily that any dynamic condition may be obtained and that faithful reproduction of operational use of the engine is possible. The dynamometer control system receives commands from the main controller in the form of analog voltages. Those voltages are variable under program control from -10 to +10 v d-c in step increments of 20 mv or multiples thereof. Since controller command switching is several orders of magnitude faster than the dynamometer control system response, no transients are experienced, and the incremental control voltage output appears as nearly a smooth curve during acceleration-deceleration runs.

Self-Check and Reliability - The degree of success achieved with any automatic test system is in great measure determined by the degree of operator confidence in the system and its results. This degree of confidence is directly

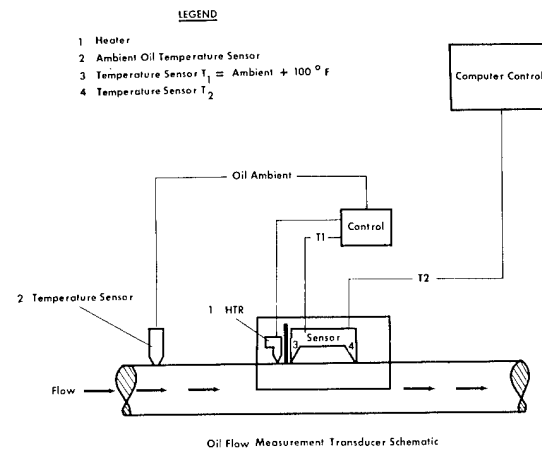


Fig. 17 - Oil flow measurement transducer schematic

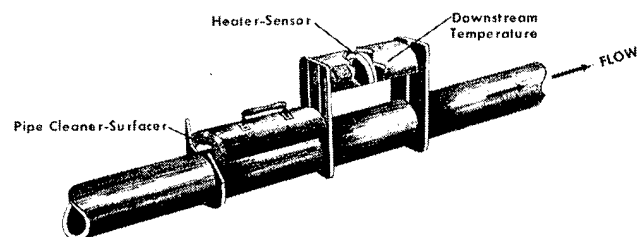


Fig. 18 - Oil flow sensor; automatic checkout system for combat vehicles

proportional to the self-check and reliability characteristics of the system. Major factors in the economic value of the automatic test system are the features that have been incorporated to facilitate maintenance, since these contribute directly to the ratio of up-down time of the system. The discussion that follows describes some of the characteristics that have been built into the test system to increase operator confidence and improve the maintenance aspects of the equipment. In general these features can be divided into two groups: those which deal with the self-check capability and those concerned primarily with reliability and maintenance.

On input of program information, either from the bulk storage or the Flexowriter, the computer will automatically indicate proper entry and absorption of data by the use of a programed check sum. This check sum compares the total number of information bits transferred with the total number of bits stored in the computer. In the event of a discrepancy, the computer indicates a system error. In addition, parity checks are used in information transfer to and from the bulk storage medium.

If measurement data brought into the test system via the commutator are within proper tolerance, the test program continues. However, if an error or out-of-tolerance measurement should be detected, an automatic self-test routine is initiated. This self-test routine operates as follows: The eight-line input group remains connected to the transducers. The computer sends predetermined digital control data to the digital-to-analog converter, which provides an analog signal equal to the value that should have been read. The output analog signal is routed automatically by the crossbar switch to the input line on which the out-of-tolerance reading was detected. Thus the analog self-test signal is superimposed on the actual measurement. The analog-to-digital converter ground input is switched from the common ground used with the transducer signals to a floating ground used with the self-check test signal. This technique then permits the transducer signals to remain undisturbed, and the system self-checks the performance of all the relays in the switching, multiplexing equipment, the analog-to-digital converter, the digital-to-analog converter, and the input routine of the computer.

After the self-check test voltage is evaluated and found to be correct, the out-of-tolerance data are considered correct, and the system returns to normal operation. The transducer data are properly evaluated, and the pertinent diagnostic and logistical data are printed for the operator. The automatic test routine described above is accomplished in less than 1 sec.

An additional self-check feature is the evaluation of data from both redundant transducers and dependent transducers. A bad reading from a particular transducer is checked against readings from other transducers whose output is affected by the particular physical parameter being measured. For example, if a temperature transducer reads a high tempera-

ture, the output of transducers located in physical proximity will be affected. The computer program will proceed to examine readings from these additional transducers before accepting the validity of the measurement under question.

A number of features have been designed into the system to facilitate maintenance and permit easy location of malfunctions. Some of these features are described briefly below.

The automatic test system has been provided with several malfunction isolation routines which can be used by the operator to check automatically a number of the system major assemblies.

Many of the major assemblies have indicators and test modes that facilitate malfunction isolation; for example, the time-varying signal measurement and magnetic tape control assemblies contain provision for manual check on all logic equations and signal voltages.

The crossbar switch has an associated light display that completely indicates its operational state.

The major units of the system are interconnected through a unique patching system. The interconnecting cables are wired to an etched circuit card connector which contains test points for all the lines. These points are coded and are readily accessible for manual monitoring of signals within the system.

A number of recirculating loops are used as registers in the computer, to provide instructions and program control. These are displayed in a special neon register and are used for maintenance and program debugging. By means of special test routines, it is possible to check the complete transfer of information and control within the computer and locate malfunctions with considerable rapidity.

Although the equipment described in this paper is not completely militarized, every attempt was made to select components with excessive design safety margins that would enhance the reliability of the equipment. For example, mercury-wetted relays are employed throughout and redundant contacts are provided for possible echo check operation.

ENGINE TEST AND ANALYSIS APPROACH: Test Philosophy - As previously stated, most authorities agree that full load testing is the only positive method of determining if a vehicle can perform its design mission. However, certain faults are more evident at less-than-load conditions. It was therefore decided to impose three load-speed conditions on the engine, to obtain maximum diagnostic information. These points were selected so as to obtain the optimum speed for valve action and ignition diagnosis, the torque peak, and the horsepower peak of the engine performance curve.

Obviously, to diagnose faults within an engine automatically, numerical data representing both "good" and "bad" engines must be obtained. To this end, a series of controlled tests were run on a random sample of engines taken

from the total available population. These tests, performed at Detroit Arsenal's Power Plant Laboratory, were of two types:

1. Accelerated life to record the history of an engine from the new condition to the completely worn-out condition
2. Check tests of preliminary fault indicators by artificial introduction of known malfunctions

From the data compiled in this series of tests plus manufacturers' data and evaluated field reports, tables of "goodness criteria" were prepared from which tabulations (which we have called "Truth Tables") have been established. This effort proved the assumptions made at the outset of the project as to which measurements were truly parameters of performance. The next step in the mechanization of the automatic test was the preparation of flow diagrams.

Functional Description - Flow diagrams have been prepared to show graphically the desired controller functions to the programmer, who, in turn, translates these functions into machine language. Shown in Fig. 19 is a simplified version of the complete test routine.

After an initial warm-up of the system, an automatic check of the temperature and pressure transducers is initiated by the controller before the engine is started, to determine if transducer circuit adjustments are required. All necessary adjustments are presented to the operator in the form of a type-out. If no adjustments are required, the engine is then started. During the first part of engine warm-up (at idle), all transducers and their associated electronics are checked for proper operation; nonoperation of certain critical transducers will cause an automatic engine shutdown. Of the remaining transducers, appropriate type-outs will show which circuits need attention. If repairs to the transducers and electronic components are indicated by type-out, the self-check routine will be run again to verify proper operation.

After the self-check has been completed satisfactorily, a fast idle, no load condition is set on the engine for the remainder of the warm-up period. Engine oil pressure and oil temperature are monitored as warm-up indication, oil pressure as a safety monitor, and oil temperature to determine when the engine has attained warm-up. Engine speed and load conditions are also checked. If the engine fails to obtain operating temperature after a fixed length of time, a type-out calls for an oil cooler check.

After engine warm-up, an acceleration and deceleration run is initiated to determine ability of the engine to obtain maximum speed. The first engine speed and load conditions are set and checked, allowing time for stabilization of such conditions as engine performance, temperature, and pressure. Data from all engine sensors are sampled several times and averaged, to reduce any effects of unwanted transients. A safety monitor check is then run to check against critical faults and to see if the original set of operating conditions has remained unchanged. All data voltage readings

are then translated into actual measurement units by the controller, using equations stored in its memory. These measurements are then compared with standards.

Those engine parameters that indicate critical engine malfunctions will cause an automatic shutdown. Assuming no critical engine parameters out of tolerance, computations are performed by the controller to obtain performance figures such as corrected horsepower, air-fuel ratio, volumetric efficiency, brake specific fuel consumption, and oil consumption.

Using performance figures and other stored engine measurements, the controller determines what malfunctions are indicated by those engine data that are out of tolerance. Fig. 20 is an example of a typical diagnostic chart, showing how several engine malfunctions each have a unique set of indicators. If the diagnostic analysis shows any faults such as bent connecting rod or defective oil pump, that would cause damage to the engine if testing were continued, a shutdown is effected, and the results, based on data obtained, are typed out.

After the diagnostic analysis has been run by the controller, a transducer self-check is initiated by checking the operation of all transducers, to determine the validity of the diagnostic analysis. Any noncritical transducer failure will cause the controller to modify the diagnostic analysis so that as much analysis as possible can be obtained from the engine performance data. New engine speed and load conditions are then set and checked, data sampled, and com-

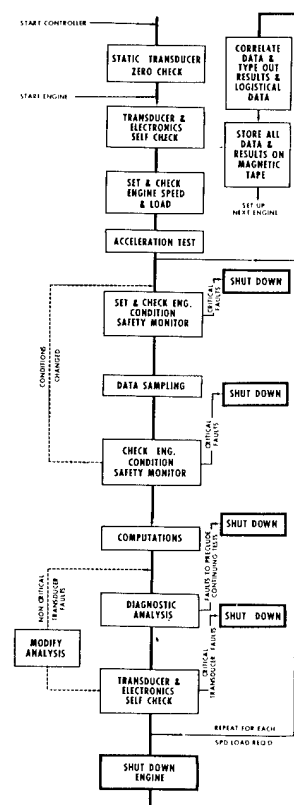


Fig. 19 - Simplified test routine

Table 2 - Sample Output Format of Required Repairs

<u>Malfunction</u>	<u>Code</u>	<u>Ord. Stock No.</u>	<u>Fed. Stock No.</u>	<u>Man. Part No.</u>	<u>Ord. Part No.</u>	<u>Quan.</u>	<u>Repair Ref.</u>
Main / Con Rod Bearings Worn		G244-7744597	2805-774-4597	CO-301750	7744597	12	TM9-7009-1 section VIII par.103c, 104c pp. 190, 192
		G244-7744598	2805-774-4598	CO-302409	7744598	2	
		G244-7767524	2805-776-7524	CO-301943	7767524	24	
Con Rod # _____ Bent				CO-515453	8357878	12	TM9-7009-1 section VIII par.103c p. 190
Broken or Strip- ped Cooling Fan Drive		G262-8344515		CO-525255	8344515	2	TM9-7009-1 section X par.112 p. 199
Pistons / Rings and Cylinder Walls Worn				CO-515212	7403133	12	TM9-7009-1 section V par.87 p. 163
		G251-7346610	2805-734-6610	CO-518090	7346610	12	
Slipping Cooling Fan Clutch		G262-8344515		CO-525255	8344515	2	TM9-7009-1 section IX par.108 p. 199
Defective Oil Pump		G244-7744620	2805-774-4620	CO-515652	7744620	1	TM9-7009-1 section III par.68 p. 132
Defective Oil Pressure Regulator		G244-7521-774	2805-752-1774	CO-516446	7521774	1	TM9-7009-1 section III par.78 p. 151

and incipient failures. The inherent speed capability of the controller makes this process practical even in a short-term test.

Programing Approach - The sequence of acquiring data by means of the transducers and the method of data evaluation to indicate faults in the unit under test are known as a test routine, or test procedure. The translation of the test routine into computer commands for use by the automatic test system control is known as programing. The sequence of computer commands obtained by programing is called a test program. The present computer test program has been written in the form of subroutines; that is, the functional program described has been broken down into repetitive operations that are prepared in subroutine form and called in as needed by a single command word. This method not only simplifies the actual preparation but also allows maximum flexibility in effecting changes in the overall format. It is anticipated that these subroutines will form the nucleus of a growing library which will enable rapid assembly of complete programs for checkout of a variety of equipments.

The actual test routine must be prepared, based on an analysis of the unit under test, by skilled engineers and malfunction diagnosticians. It is difficult to minimize either the importance or the difficulty of this task. In fact the degree of success achieved with the test system will depend in great measure on the skill and sophistication with which the test routine is developed. However, there exists a second, highly important, time-consuming, and costly step before the test routine may be employed; that is, the programing of the test routine.

The programing of the test routine for the test system and its validation is normally a difficult and costly procedure, requiring many man-hours of effort of the most skilled programing personnel. These personnel must not only possess an intimate knowledge of the workings of the test system but must also be highly skilled in the art of programing itself and have some background in the preparation of test routines.

In order to lessen the difficulties imposed by programing, work is presently under way on a process of automation for this problem. This process is broken down into two major tasks. One is the development of a pseudo-language for writing the test routine; the second is a compiler program that can be used to transform the test routine written in the pseudo-language into a test program.

The pseudo-language is essentially a restricted English vocabulary together with syntax (sentence structure) and grammar principles for its usage, in which the test routines are written. While the test routines will appear to be written in the conventional English language, they now possess a regularity and format that make possible the automation of the remaining process.

In order to automate the preparation of the test project from this point, a special compiler program is required. This compiler program, which is constructed for a specific

large-scale digital computer, accepts the test routine written in the pseudo-language and reduces it automatically to a completed test program for the automatic test system. In the process, the program is not only optimized with respect to speed and memory capacity required, but it is also completely checked and verified to ensure that there are no errors, duplications, or inconsistencies present.

Utilizing this automated process will make possible significant cost and time savings in the initial preparation of test programs and will provide for efficient handling of modifications required for either improved test procedures or minor model changes in the units to be tested.

MILITARY-COMMERCIAL APPLICATIONS

MILITARY - Present Ordnance Corps studies on extending automatic systems to field use have proved that such equipment would be not only technically feasible but would also significantly enhance the tactical readiness capability of the front line troops by ensuring "really ready" equipment. At the same time it has been shown that significant cost reductions and reduced skill levels of maintenance are possible. Fig. 23 shows an artist's conception of the field checkout system applied to trucks. This set would use a portable chassis dynamometer and a militarized truck-mounted version of the controller described previously. Fig. 24 shows typical transducers to be used in such a checkout system.

COMMERCIAL - The basic test set required in a commercial fleet-type maintenance shop would be somewhat reduced from the equipment shown in Fig. 2 (Letterkenny installation). Considerable growth potential has been designed into the Letterkenny system; in commercial systems the access problem would be considerably simpler than that just described. Local rules during normal maintenance checks would even permit the addition of some transducers into the engine and into the transmission and cooling system, axles, and so forth during the inspection period. These would remain on the vehicle throughout its life. They would add a little to the initial installation time but would considerably reduce the subsequent test time.

There is a very close relationship between the automotive industry and the automotive equipment developed for the military services. The military is attempting to design a family of vehicles that will require considerably less maintenance than ever before by, during maintenance, actually disregarding the major defective component. How soon this will be accomplished and phased into the system is not known at this time. The life of a commercial vehicle has been based on somewhat different ground rules.

Maximum utility requires that the inspection and diagnosis should be thorough, complete, and correct. In addition the system should be able to present an estimate or a probability of the vehicle reaching a destination with a given load. This should be based on its past history and conditions during test. The current system has some complexity

due to lack of properly designed transducers and lack of proper criteria of goodness. The study of automotive vehicles, their characteristics, and signatures of each of the major components relative to their actual life is under way and will continue for several years. The results of these studies should drastically simplify the instrumentation portion of the equipment. An artist's concept of a possible in-

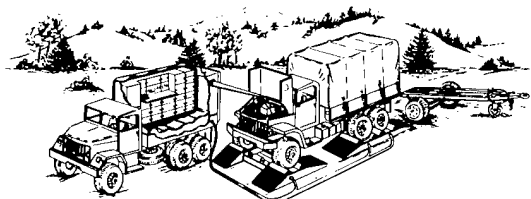


Fig. 23 - MAIDS automotive subset inspecting wheeled vehicle

the specific vehicle between signal received and malfunction. The early initiation of a data-gathering program could very rapidly provide this information if conducted on an industry-wide scale with these data in hand. It is estimated that a test set for automotive equipment would cost approximately \$100,000. Basic laboratory test equipment for the oil analysis system (with the requirement for sealing the oil system), and highly skilled chemists to operate the equipment and provide analysis of the oil, costs at least \$100,000 plus salaries.

Military development programs will soon start to require a number of built-in transducers to provide key data for readiness testing of the vehicle. Fleet owners and automotive men, as customers of automotive equipment manufacturers, could also aid this effort by discussing, questioning, and requesting certain types of transducers to be built into the engines upon purchase. It is believed that a fairly

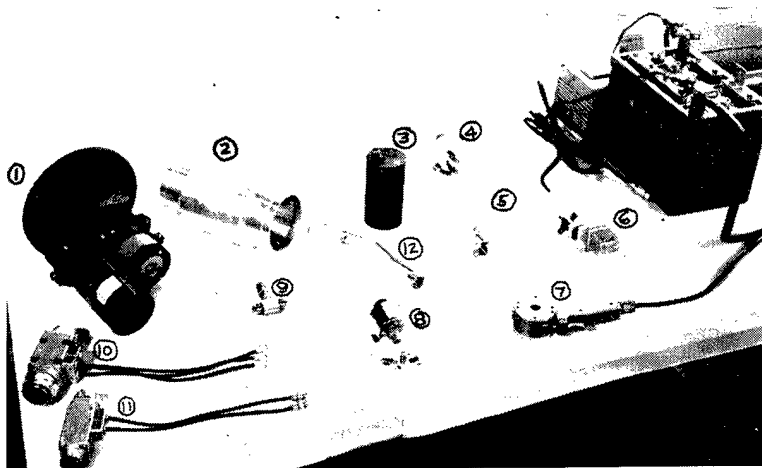


Fig. 24 - Typical transducers; (1) tachometer and shaft position indicator; (2) flow tube (air fuel); (3) pressure transducer, weather station; (4) typical differential pressure transducer; (5) valve vibration pickup; (6) air velocity indicator; (7) current measurement probe; (8) pressure transducer and fitting, manifold pressure; (9) turbine flow meter; (10) electrical connector, magnetos and sending unit; (11) electrical connector, magnetos; (12) spark plug temperature transducer and bracket

stallation is shown in Fig. 25. The pictorial system involves a standard chassis dynamometer of the type familiar to all, together with a console that would house a controller similar to the type described previously. Shown also is a small instrumentation package in place over the engine of the tractor. The instrumentation package would be modularized so as to adapt to different makes of vehicles and would contain those transducers that are commonly applicable to many vehicles but which are not economically feasible to build in. The design of this equipment is not "Cloud Nine" - it is well within the state of the art today. The important information lacking, however, is the correlation for

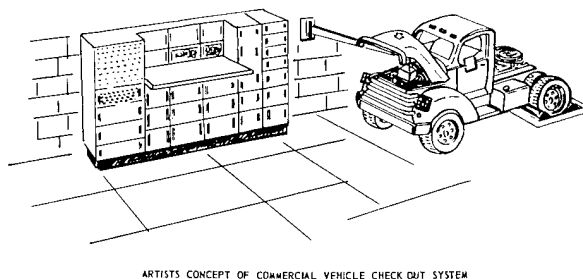


Fig. 25 - Artist's concept of commercial vehicle checkout system

inexpensive set of transducers can be designed into the engine and power pack during manufacture at an increased cost in the total engine and drive system of \$500 to \$1000. As the trend in tractor vehicles changes from straight internal combustion to diesel engines (and possibly to future turbines), the basic test equipment will remain unchanged. The computer-controller, its switching, and control equipment would be exactly the same as that used today. The difference would be in the internal statement of the problem; that is, the program used to control the test. In all probability, brackets for housing or mounting the transducer (if the external clip-on type were used) would have to be changed as the new engines and transmissions became available. The requirement of the user could force the engine manufacturers to build these transducers into the new equipment.

Field tests with a more complex digital computing system operable and maintained by nonskilled military personnel have established beyond a shadow of a doubt the ability of this equipment to be maintained on a similar basis commercially without causing maintenance problems of its own (that is, the cure would not be worse than the ailment).

The system described, or an equivalent commercial type, would also have the ability to handle other peripheral or auxiliary equipment within the vehicles or trucks; that is, refrigeration equipment can be tested, electrical signal equipment can be checked, and if the trend holds, even radio dispatching equipment for the vehicles can be tested by the same test set. In the case of electronic testing, stimuli equipment would have to be provided, but this equipment would still be under control of the test set and would not require any special training of test personnel. Further,

there is a high probability that a computer utilizing commercial components and designed to have sufficient arithmetic capability of performing analysis and diagnosis of this class of problem could substantially reduce the cost of the test set during the next few years.

The computer-controlled test set also makes a powerful factory test and inspection tool. With this device, complete performance and test data on an engine can be accumulated as it is run in. These data could then be sent with the engine (transmission) and would represent the "initial" test data. Moreover, with this equipment, engine manufacturers would be less reluctant to supply complete performance data.

CONCLUSION

The military requirements for vehicle maintenance by unskilled personnel, spurred by the diminishing availability of skilled mechanics in civilian reserves, has provided the incentive and direction to develop the computer-controlled diagnostic equipment described in this paper. The growing civilian dependency on truck transportation of commodity items has caused an ever increasing expansion of the trucking industry. As in all competitive business, reliability and dependability of delivery as well as cost are items considered by manufacturers. Vehicle performance and vehicle maintenance are factors governing truckers' profits and losses. The incentive for simplified maintenance and possible life prediction appears great. The engine, transmission, and vehicle manufacturers should be encouraged to take advantage of the developments described in this paper and should apply them to civilian use.